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# Mitigation of Laser Damage on National Ignition Facility Optics in Volume Production


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## ABSTRACT

The National Ignition Facility has recently achieved the milestone of delivering over 1.8 MJ and 500 TW of 351 nm laser energy and power on target, which required average fluences up to 9 J/cm$^2$ (3 ns equivalent) in the final optics system. Commercial fused silica laser-grade UV optics typically have a maximum operating threshold of 5 J/cm$^2$. We have developed an optics recycling process which enables NIF to operate above the laser damage initiation and growth thresholds. We previously reported a method to mitigate laser damage with laser ablation of the damage site to leave benign cone shaped pits. We have since developed a production facility with four mitigation systems capable of performing the mitigation protocols on full-sized (430 mm) optics in volume production. We have successfully repaired over 700 NIF optics (unique serial numbers), some of which have been recycled as many as 11 times. We describe the mitigation systems, the optics recycle loop process, and optics recycle production data.



**Keywords:** National Ignition Facility, optics, laser damage, laser damage mitigation, laser damage repair


## 1. INTRODUCTION

The National Ignition Facility[1] (NIF) at Lawrence Livermore National Laboratory requires a large area of high quality optics which can withstand repeated high energy laser shots. The system meets and exceeds its design specification of 1.8 MJ of total energy[2] delivered on target with a 3 ns pulse duration at 351 nm "3ω" wavelength and has been successfully operated above 500 TW[3]. For 192 beamlines with 35 cm square apertures, the mean fluence is around 8 J/cm$^2$ at the final fused-silica optics. Figure 1 compares the total beam area and mean fluence to other high energy pulsed laser systems—NIF has about 7.5X more area and about 12X the mean fluence. The shaded area encompasses the conditions for routine NIF laser shot operations. The NIF 3ω energy specification of 1.8 MJ required an order of magnitude increase in operating fluence over previous Inertial Confinement Fusion (ICF) lasers. The vertical band at 4 J/cm$^2$ is the approximate damage growth threshold fluence, beyond which initiated laser damage grows with each shot. Routine operations above the threshold require the ability to manage the resulting laser damage with either replacing, refinishing, or repairing the optics. This paper discusses our demonstrated ability to mitigate (repair) laser damage on NIF optics which allows NIF to operate above the damage threshold to repeatedly deliver 1.8MJ on target and therefore meet its programmatic missions.

The NIF 1ω laser at 1053nm operates well below the damage initiation and growth threshold and has proven itself to be reliable even without optics exchanges. It is only the couple of optics downstream of the frequency conversion in the Final Optics System that must withstand high fluences of 351 nm laser light (Figure 2). Both optics are made of inclusion-free fused silica: the wedged focus lens (WFL) both focuses the beams onto the target and refracts unconverted 1ω and 2ω light off target; the grating debris shields (GDS) protect the other final optics from target debris and diffract 0.1% of the 3ω light into an energy diagnostic system. Figure 3 shows two wedged focus lenses undergoing final QA inspection. The optics are assembled in the kinematic mounting frames used in the NIF; the assembly is referred to as a line replaceable unit (LRU).

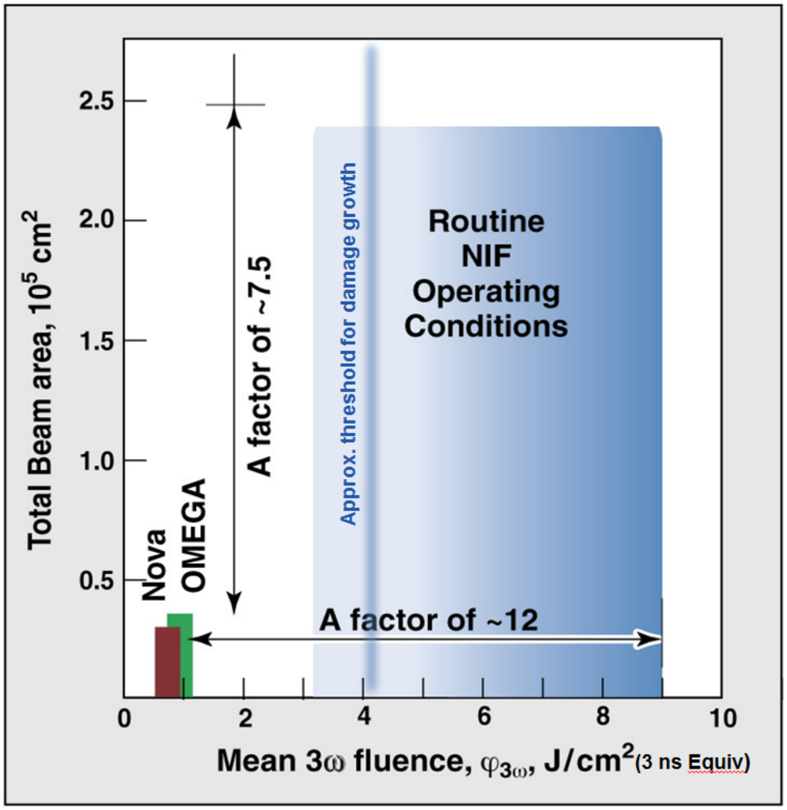



**Figure 1.** Routine NIF operations require operating at fluences well above the laser damage growth threshold.

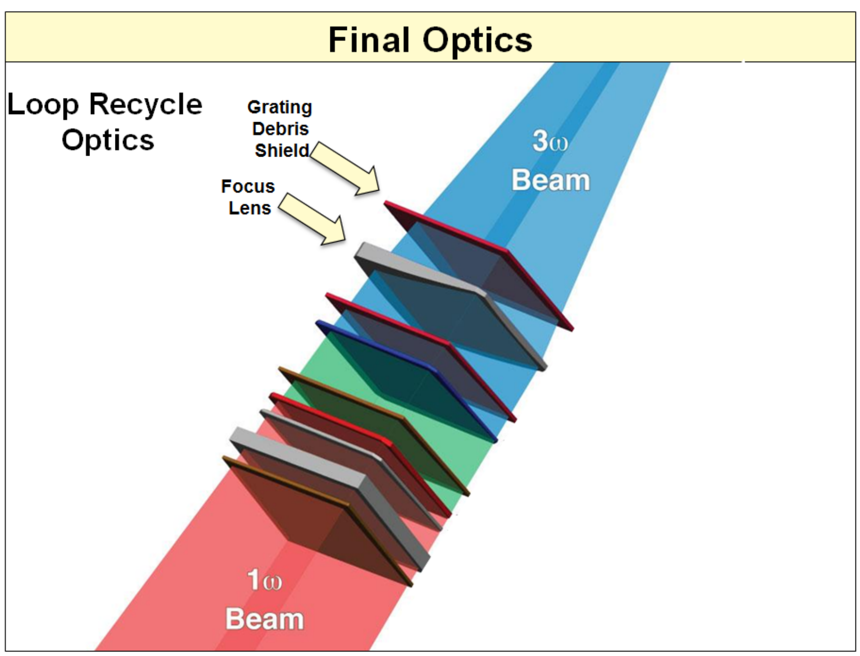



**Figure 2.** The wedged focus lens (WFL) and grating debris shield (GDS) optics are exposed to high fluence 3ω light and are the key Recycle Loop optics.

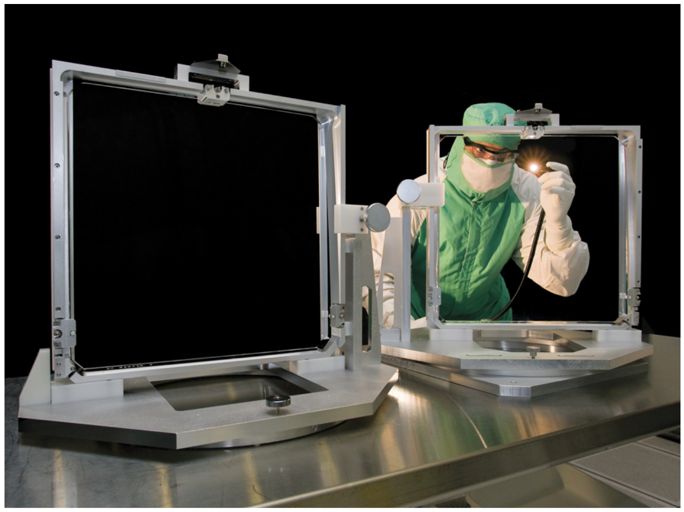


**Figure 3.** Wedged focus lenses assembled in optomechanical kinematic mounts undergoing final QA inspection

Several techniques have been investigated for using $CO_2$ lasers to mitigate, or repair, laser damage on fused silica optics.[4-24] Our preferred technique is the Rapid Ablation Mitigation (RAM) process described previously[25]. The RAM process uses a $CO_2$ laser to remove damaged material as depicted in Figure 4. The pulsed $CO_2$ laser beam is focused to a 100 μm spot size and raster scanned across the damage site in a circular pattern to remove the damaged silica and leave a clean and smooth cone-shaped pit. To prevent re-initiation of damage when the optic is re-installed on NIF, it is critical that the cone be large enough and deep enough to remove all residual cracks and that the site be clean of ablation debris re-deposited on the surface during the process. The shape of the cone must also be carefully controlled so that the feature does not intensify the NIF beam and cause damage on downstream optical surfaces. For example, rims on the perimeter of the cone are known to be particularly deleterious. We have developed several versions, or protocols, of the RAM process to meet these requirements for damage sites of different size bins, each of which is tailored for either the input or exit surface.

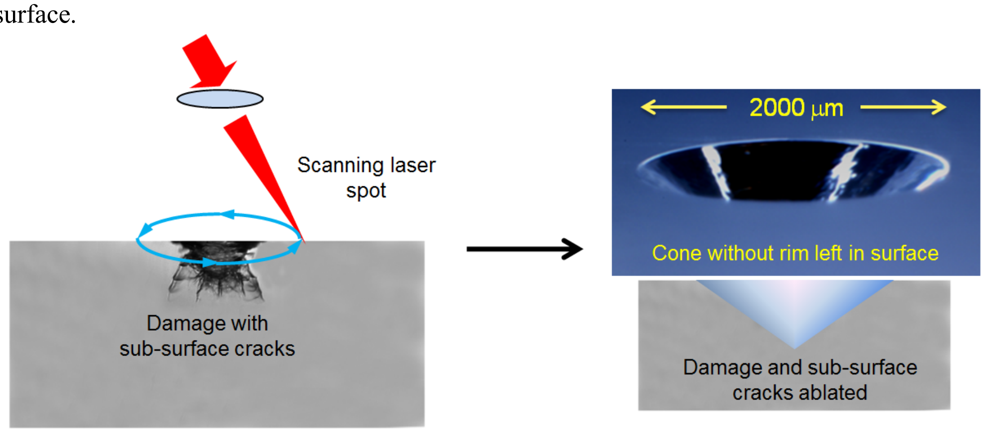



**Figure 4.** The Rapid Ablation Mitigation (RAM) process uses a $CO_2$ laser to remove damaged material

## 2. SYSTEM DESCRIPTION

The optic mitigation stations are engineered systems which integrate several subsystems required to inspect the damage sites and perform the mitigation process. Figure 5 shows a mitigation station with a grating debris shield optic mounted vertically on an X-Y translation stage. Various instruments are mounted on individual Z stages on both sides of the optic. On the forward table side of the optic are a non-contact profilometer used to measure the Z location of the optic surface, the focus lens assembly of the $CO_2$ laser beamline, and an inspection microscope. On the reverse table side of the GDS optic are a process microscope used to monitor the mitigation process and an illumination source for the forward inspection microscope. The Optics Mitigation Facility contains four mitigation systems, each of which is housed within a class 100 cleanroom to maintain the cleanliness of the optics.

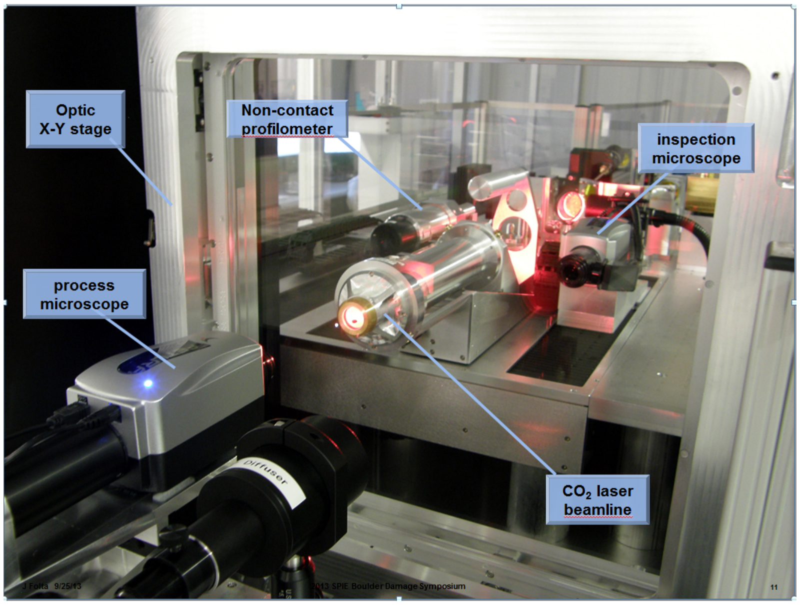



**Figure 5.** A mitigation station with a grating debris shield optic mounted vertically on an X-Y translation stage

**Mitigation: Concept of operations**

1. **Load optic**
   The optic is loaded onto the X-Y stage carriage and rotated so that the exit surface faces the instruments on the forward table. The optic is mounted in the same LRU kinematic frames as used to install it into the NIF system. The LRU is transferred directly from a recycle loop transport case, which is used to cleanly and securely transport and install optical LRUs without the need for manual handling of the LRU.
2. **Locate surface with non-contact surface probe**
   The optic is translated in front of the non-contact surface probe which is used to measure the z-position of five different locations of the optic. The data are used to fit the spatial position of the optical surface so that the other instruments can be automatically focused. The surface fit is accurate to within about 20 µm which is well within the tolerance needed to keep the microscopes and mitigation laser focus lens in focus without operator adjustment. The motion controllers are programmed so as the X-Y stage positions a damage site in front of an instrument, the Z stage for that instrument automatically drives it to focus. The curved input face of the WFL requires that the surface profile data be fit to the same aspheric equation as used to manufacture the lens.
3. **Register X-Y coordinates to fiducials**
   The optics have a pattern of drawing-specified fiducial marks outside the aperture illuminated by the NIF beams. The fiducial pattern is used as the reference for X-Y coordinates of individual damage sites which are inspected on line with the Final Optics Damage Inspection (FODI) system. The inspection microscope is used to locate the fiducial positions which allows calculation of the X-Y-Θ translations needed to convert between stage coordinates and FODI optics coordinates.
4. **Microscopic Inspection of sites on hit list; make mitigation decision**
   The inspection microscope is used to inspect the locations which have been identified (by FODI or other metrology) as having growing damage sites. The microscope is scanned through the bulk of the optic to the opposite side to determine the full extent of the damage. The operator examines, sizes and centers the site, and judges if damage mitigation is required. Inspection is performed for sites down to a size of 50 µm, the minimum size at which FODI can reliably resolve between growing and stable damage sites. Images of the sites are captured.

5. **Mitigate sites**
   After all sites have been inspected, the operator verifies that the mitigation laser system operates within tolerance. The sites are automatically mitigated while the operator monitors the process with the lower resolution process microscope on the reverse table looking through the back side of the optic. The laser control system continuously monitors that the pulsed laser system operates within tolerance.
6. **Post mitigation microscopy**
   The inspection microscope on the forward table is used to collect images of all the mitigated sites. The operator examines the images to confirm that all remnant damage and cracks were removed. Images of the mitigated sites are captured.
7. **Flip optic**
   The optic is translated back to the loading position to allow the operator the rotate the optic so that the input surface faces the forward table. Note that steps 2 through 6 are “hands-off” operations performed completely with the operator in the control room. Isolation of the operator from the mitigation system improves the safety of the operator from laser hazards and maintains the cleanliness of the optic.
8. **Repeat steps 2-6**
   Steps 2 through 6 are repeated for the input surface of the optic. During inspection of the second surface, scanning through the bulk of the optic is not required.
9. **Unload optic**
   The optic is translated back to the loading position where it is unloaded back into a protective loop case.

The primary responsibility of the mitigation station operators is to analyze the microscopy images to categorize the damage sites and use a rule set to select the specific mitigation protocol to be applied. Figure 6 shows the control computer user interface with a damage site centered in the crosshairs. Operators are trained to discern among laser damage, contamination and other flaws, the latter two of which do not benefit from mitigation. The operators can classify the site into different classes and enter comments about unusual sites. If mitigation is required, the operators select from among five different protocols which are summarized in Table 1. The protocols range in diameter from 360 to 2000 μm and in depth from 150 to 350 μm. The largest protocol requires 5 minutes while the shortest, at only 15 seconds, is barely long enough to gather meaningful statistics on the laser operation. Table 1 also shows images of typical damage sites mitigated with the protocols. Note the absence of a large diameter protocol for the input surface. Downstream modulation of the NIF beam which damages the exit surface of the optic have hindered development of larger input surface protocols.

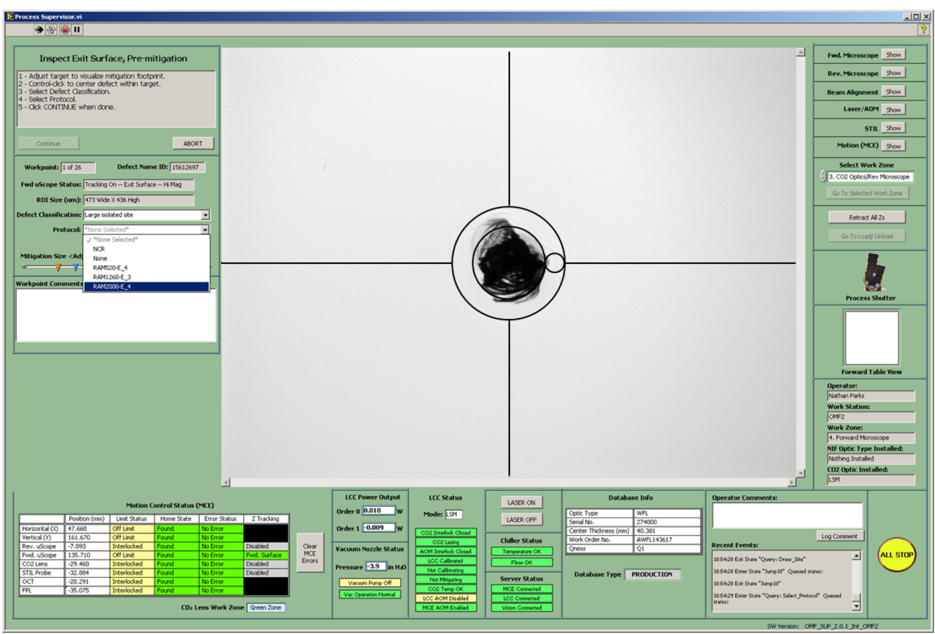



**Figure 6.** The user interface for microscopic damage site analysis and protocol selection

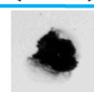
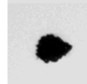
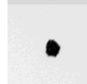
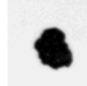
| Protocol name | Protocol Diameter µm | Maximum Damage Site Size µm | 500 µm | Optic Surface | Time to mitigate min:sec |
|---|---|---|---|---|---|
| RAM2000 | 2000 | 800 |  | exit | 5:00 |
| RAM1260 | 1260 | 349 |  | exit | 1:18 |
| RAM520 | 520 | 149 |  | exit | 0:15 |
| RAM360 | 360 | 180 |  | input | 0:51 |
| RAM600 | 600 | 320 |  | input | 0:22 |

**Table 1.** Five mitigation protocols are available, depending on damage site parameters

## 3. RESULTS

The Optics Mitigation Facility repaired its first wedged focus lens in August of 2009. Since then, the protocols, procedures, hardware and software have been improved to increase the efficiency of the operation. In the autumn of 2012, the OMF used a 4-machine, 2-shift operation to support a 40 optic/week exchange rate, which allowed the NIF to repeatedly provide 1.8 MJ system shots during the National Ignition Campaign. (Figure 7.) Optics can be recycled and reinstalled on the NIF many times with no degradation in laser performance. Figure 8 is a histogram of the NIF WFL and GDS populations as a function of how many times they have been recycled. One WFL has been recycled 11 times. The remnant cones from the mitigation process represent such a tiny fraction of the area of these rather large optics that even hundreds of cones on an optic are acceptable. Figure 9 is another histogram of the optic population as a function of the number of mitigation cones. The optics with more than 400 mitigation sites have a total obscuration far below the NIF specification of 1%.

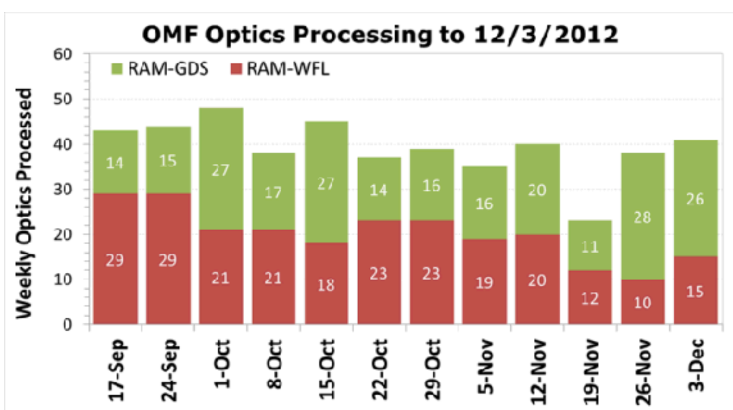



**Figure 7.** The Optics Mitigation Facility (OMF) consistently mitigated 40 optics/week using the Rapid Ablation Mitigation (RAM) technique to support repeated 1.8 MJ NIF shot operations. The GDS and WFL optics types are shown in Figure 2.

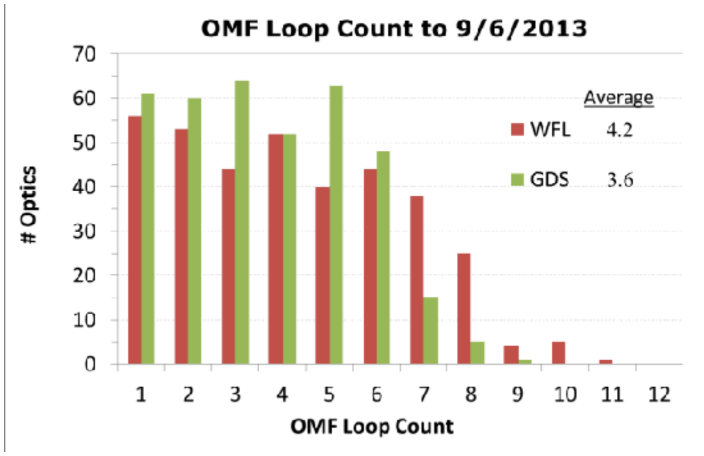



**Figure 8.** Optics have been recycled and mitigated as many as 11 times through the Optics Mitigation Facility (OMF).

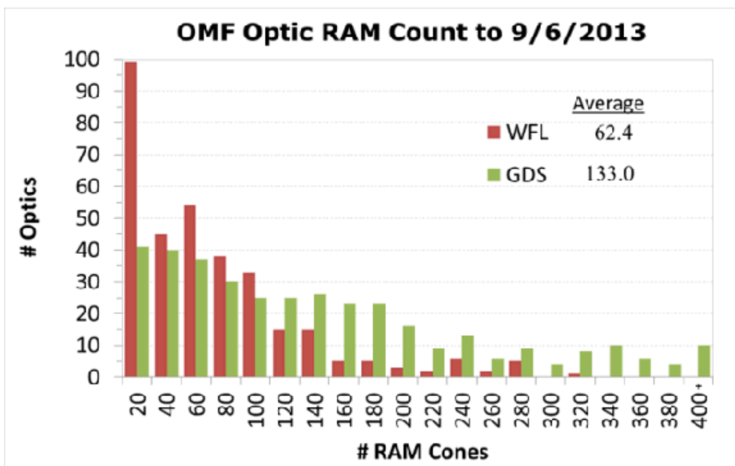



**Figure 9.** Optics with hundreds of mitigation sites have a total obscuration far below the NIF specification of 1%

Table 2 presents key statistics of the recycle production loop. The most important statistic is that 98% of the damage sites fit within our mitigation ruleset and can be repaired. Since we do not re-install any optic with 3 or more unrepairable sites, the recycle yields are a strong function of the fraction of sites which are mitigable. For example, if only half the sites were mitigable the optics mitigation facility would serve no practical purpose. However, with the 98% site mitigability, the recycle yields for the wedged focus lens and grating debris shields are 93% and 85%, respectively. Another key statistic is the re-initiation rate repaired sites: of mitigated sites, fewer than one out of a thousand will damage again after reinstallation on the NIF. Once again, this value must be near perfect for the recycle loop to function. As of September 2013, nearly 3000 optics have been recycled into the NIF.

**Table 2.** Mitigation Statistics: show that nearly all damage sites are mitigable, and repaired sites almost never re-initiate

| | |
|---|---|
| **Fraction of damage sites that are mitigable** | **98%** |
| **Yield for wedged focus lens** | **93%** |
| **Yield for grating debris shield** | **85%** |
| **Re-initiation rate** | **< 0.1%** |
| **Total optics recycled** (as of Sept. 2013) | **2867** |

## 4. CONCLUSIONS

1. Recycling of optics with mitigation of laser damage on NIF optics in volume production enables NIF to operate the 3ω optics above the laser damage threshold and perform sustained high energy shot operations.
2. We have recycled nearly 3000 wedged focus lenses and grating debris shields to support NIF shot operations.
3. Two years of process improvements have resulted in an efficient, high yield, sustainable optics recycle loop.

For future work, we are developing methods to mitigate laser damage on mirrors and the KDP frequency conversion crystal optics.

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